Literary Review

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Developments in the Research and Testing of Clothing Worn in Polar Environments between 1960 and 2008

Abstract

Clothing worn in polar regions has been subjected to investigation and development for the purpose of improving comfort, practicality and efficiency for those wearing it. Extreme cold weather and harsh climatic conditions provide life threatening scenarios for those living and working on the ice. Monitoring and testing of clothing has advanced our understanding of the mechanics of heat production and loss, thermal insulation, vapour transmission and external environmental variables. Research and testing of fibre and fabric have led to the development of man-made fibres, design improvement and practicality in the field. Testing procedures have changed over the years where equipment, technology and procedures have improved the quality of research results from subjective to objective standards. As polar environments become more attractive and accessible places to work or play in, effective extreme weather clothing remains a life-saving necessity.

Introduction

Man is an inquisitive beast, always striving to push the boundaries and learn more. Often this urge to discover has led him to environments that are not immediately hospitable - space, deep sea, deserts or extreme cold. Polar and mountain areas provide very real challenges as they put man at the extreme end of his survival capabilities. Living and working in these environments require specific adaptations and developments in terms of thermal insulation and maintenance of core body temperature. Our growing knowledge of heat production and loss, the role of external environmental factors such as temperature, humidity, wind speed, and clothing values such as layering, fibre, fabric, finish and fit ensure the safety and comfort of those living there. Early polar expeditions used clothing largely composed of natural fibres – wool, fur, cotton, silk and linen, using the experiences borrowed from Native peoples. The next source of duplication came from military clothing issue as they had pushed the development of design in the extreme cold for troop training and survival. Finally, real attempts were initiated to test and model man-made fabrics and design to investigate the properties of insulation. Testing continues today and fabrics are becoming thinner, lighter, warmer and more comfortable as a result.

This review will examine and critique, from a variety of sources, the growth of knowledge and testing methodologies for heat conduction and convection, insulation and layering properties, fabric design and psychological parameters.

Heat Production

Heat is produced in the body through metabolic activity and when the body exercises the need for oxygen and nutrients to the muscles rises, thereby increasing the metabolic activity and heat liberated as a result of muscle activity. Indusheker et al (2005), cite research done by Day et al (1986) stating that metabolic heat generated by a body doing moderate work is capable of causing a 3ºC rise in temperature in 30 minutes if impermeable clothing is worn, while heavy work being done could achieve that rise in 10 minutes.

Heat Loss

Heat loss from the body occurs through a variety of mechanisms – conduction, convection, radiation, respiration and evaporation. Havenith (1999) summarises these mechanisms by stating that for body temperature to remain stable, heat losses must balance heat production - a positive store indicates greater heat production than loss and a negative store means more heat is lost than produced.

External Environments Effecting Heat Transfer

Several external variables influence the transfer of heat from a body and include the temperature of the surrounding environment through the air, radiant and surface temperatures. If the temperature of the environment is colder than skin temperature the body will lose heat to it.

Another variable is air humidity, which determines the flow of sweat from the skin to the environment or vice versa. When air temperature is lower than skin temperature sweat will always be able to evaporate from the skin, (Havenith).

Wind speed affects the heat exchange in a body, increasing the loss of convective and evaporated heat in relation to the increasing velocity. Crow (1974), maintains “the main enemies are bitter cold and high winds, and to protect against these the soldier must have specially designed clothing,” p.1.

The final variable then, is clothing. Clothing acts as a barrier to heat and moisture transference between the skin and the environment (Havenith). Mann et al (1986), states “In extremely cold conditions, the two most important requirements for clothing

....., are the necessity of reducing heat loss from the body, and permitting the controlled transmission of moisture produced by perspiration," p.1.

Clothing Values

When considering clothing several factors contribute to the growing science of thermal insulation and vapour transference. Briefly, these include layering properties, fibre construction, fabric choice, fit for comfort and practicality and finish for construction mechanics. "Hence a very complex situation arises in thick, Arctic clothing," (Crow) p.1.

Methods/ Models

In the process of researching this review several methods and models of testing were adopted by the various authors over the time span of fifty years (the difference between the first and last articles written.) The introduction and rise in the use of mathematical formulae has taken testing from subjective feelings of comfort relative to skin and atmospheric temperatures in the 1960's, Budd (1966), through to mathematical models, computer graphics and programme use, and validated data Xu et al (1997), Seames et al (2007).

Psychological Parameters

Despite the innovation and testing that goes into developing new clothing systems for polar environments, the ultimate success of any garment is its ability to keep the wearer warm and dry and able to perform physical activity in comfort and ease, despite the conditions outside. Because of this, receiving subjective data feed-back from test personnel out in the field remains an important component - wearer satisfaction is critical for confidence in and longevity of survival apparel. Suggestions for further research in this area will be addressed later.

Research Evaluations

All of the articles and papers referred to heat loss or the ability to keep warm within their abstract or introductions. "Effective insulation and retention of body heat is the key to staying warm," p. 17. National Science Foundation (1990). "Early explorers had no special clothes to keep them warm and dry in the polar regions. Frostbite was common and many men died of exposure," British Antarctica Survey (1985). Learning how to keep warm and dry became the focus.

Convection and conduction of heat are principally transferred through the medium of clothing. A layer of clothing provides a thermal resistor for which the convective insulation depends upon how still the clothing filler can hold a layer of trapped air. Conductive insulation depends primarily upon the thickness of that clothing filler, Young (1979). Seames et al set out to quantify the thermal conductivity and thermal resistance of twelve separate insulating fabrics, noting that “the thermal conductivity and resistance of a fabric are of great importance when determining the applicability of a fabric in cold weather conditions,” p. 350. The testing was conducted in an enclosed cold box – an extension of the ASTM 1518-85 method and was rigorously done. However, these objective tests lacked any physical or situ testing experience to allow for the human subjective factor in terms of differing physical build and body mass, fitness levels, comfort perceptions or previous polar/ cold weather living experiences.

Xu et al developed a model of the human/clothing/environment-system, validated by comparisons between the simulated and experimental results under varying conditions of heat, cold, exercise, clothing and transient phases. This model therefore tried to simulate heat transfer systems under varying conditions using mathematical modelling, before conducting human subject testing to validate their model. This author believes this paper combined the best of both testing worlds in its research and was pleased to see there is scope for further testing in more extreme boundary conditions planned.

Conducted and convected heat flow is measured in a unit of resistance (read insulation), called a clo. A clo is “equivalent to the amount of clothing needed by a human at rest in an ambient temperature of 20℃,” p. 65, Stonehouse (2002). Clo is also described in mathematical terms and Young, Seames, Metje and Cena use this measurement in their papers. Cena reported the test of subjects exposed to real conditions in outdoor mountain environments measuring insulation (clo values), of sleeping bags within tents, supplemented with subjective ratings from a standardised scale. It concludes that further research into factors affecting human thermal comfort, behaviour and perceptions at high altitude, and in other environments, is needed. Seames, as reported above, used a static model to test thermal conductivities of twelve fabrics and used variability tests on these fabrics to validate their testing within statistical acceptable variances. However, no human study tests were performed to compare or contrast their findings with actual field experiments. Young, compared two fabrics using methods and equipment available at that time. Whilst the equipment and testing seem crude now, the results gave a clear indication of fabric choice for the specific conditions set for it.

The role of layering clothing has been recognised since very early pioneering polar days. The Arctic Institute of North America (1960), report details a list of clothing and a statement “ .....each ensemble incorporated the effective use of the layer principle permitting the rapid adjustment of the clothing to meet the wide range of temperature and activities......”,p.4. (Linton-Smith) detailed the clothing list for the 1968 paper, recording the experiences gained from bases at Macquarie and Heard Islands in 1948. Layering, in both summer and winter wear, was recognised and acknowledged.

More recently research has been conducted to establish the role and effectiveness of layering clothing. Fabric thickness or density is now shown to affect insulation rates, as is the size and number of air layers trapped between clothing layers, (Havenith, Crow, Seames, Xu, Yoo and Indushekar). Differing modern methods of testing, both the mathematical modelling or the standardised model testing in cold boxes or chambers, have increased our understanding of heat and vapour transfer through both fabric weave and density, and the accompanying trapped layers of air. In 1979, (Young), reported that heat conduction through fibres alone is low for two reasons – material from which the fibres are made are generally poor conductors of heat, and the area of mutual contact between adjacent fibres is small and hence fibre to fibre conduction is low. Increasing the thickness of the layer, (without adding bulk and weight), or improving the thermal capacity of a fibre will therefore improve the thermal insulation.

Modern testing has also highlighted the role of trapped air layers, be they on either side of a fabric layer and as molecules within each fibre weave. Moisture transmission within the fibres replaces the air molecules, increasing the thermal conductivity. The addition of a hydrophobic insulating layer could limit this conductivity increase, (Seames,Yoo, Indushekar). "The most important single layer of clothing is the outer layer. It should repel wind, yet allow the escape of body moisture," (National Science Foundation).

Modern testing has also re-defined our understanding of the nature and importance of fabric construction. Weave (weft and warp) tightness (allowing for differing sizes and numbers of air molecules to be trapped within the fibres), and the arrangement of the fibres (parallel versus perpendicular or disorientated, to the fabric surface), have an effect on thermal insulation properties.

Allied to this new research on layering, is the importance of vapour transmission within and out of clothing. "Inadequate clothing contributed to the deaths of Scott's party. They sweated a lot when they were man-hauling their sledges, but they could not adjust their clothing. The moisture froze, making their clothes heavy, uncomfortable and much worse at insulating," (British Antarctic Survey). ".....the thermal conductivity of the wet fibres then becomes very different from that of the dry fibres." p.1 (Crow). Water vapour diffuses through fabric from the side of higher concentration to the lower concentration. Research papers have shown both mathematical and apparatus model testing have indicated a variance in test results and conclusions. This is due to fabric density, total number of clothing layers with the associated air pockets and fibre arrangements, environmental factors (temperature, wind and humidity), sweat moisture levels (as dependent on light or heavy exercise) and fabric coatings (wind and/or water repellents). Comparisons across testing models is also inconclusive as testing conditions are often different (Indushekar), however a general overview of increasing information and data has been established in recent publications. Successful polar clothing needs to consider the diffusion properties of water in combination with the insulation properties of a fabric, (Havenith, Yoo, Crow, Young, Seames and Indushekar).

Another dimension to the success or otherwise of polar clothing is the finish of a fabric and the fit of the garments. Finish refers to any chemical(s) added to the fabric for the purpose of increasing wind chill resistance, aiding moisture deflection or evaporation capabilities or heat/UV radiation reflection or absorption properties. Thermal insulation and vapour transmission efficiency test results vary greatly when compared to non-impregnated fabrics, (Seames, Indushekar and Yoo).

Aligned to the finish properties are the seam and closure fixtures added in garment construction. Heat loss may occur at stitching seams, especially where layers of foam or down insulation are sewn between the outer shell and inner fabric, (Mann). Zips, buttons and velcro are subject to wear and tear, potential heat loss (evident from the insulated air pockets escaping), and ease of use in freezing temperatures where hands may be encased in bulky gloves or mitts. Modern polar clothing has introduced ‘flaps’ to cover long zip openings in a bid to protect and prevent thermal insulation loss over core body and limb areas. Plastic materials in zips and domes are resistant to very cold temperature ranges to prevent freezing and snapping and are included in polar garments as standard these days.

The final clothing value to consider is the fit. Fit includes the dimensions of comfort, practicality, venting, circulation, warmth, protection, weight and design. Inuit and native peoples living in polar conditions have learnt how to design and wear appropriate clothing. “The design features such as a hood, fur trim, dropped shoulder seams, pull-over design, and ability of footwear, pants, parka, and mitts to interlock all provide excellent cold weather protection,” p.84, Oakes et al (1995). Successive variations in clothing fibre, design and technology have moved polar clothing from fur to the future. The purpose of clothing has not changed, the science has. The British Antarctica Survey states that, “To do its job properly, polar clothing must

- Keep the body warm, especially fingers and toes
- Not trap sweat
- Allow free movement
- Make you feel comfortable whatever the weather.

Keeping warm, dry, mobile and comfortable is easier now thanks to the combination of natural and man-made fibres. Continual design and testing retains the forward momentum in terms of fabric innovation, light weight construction, practicality of wash and wear, protection from the elements and durability out in the field under working conditions. Layering remains the best option for effective insulation and retention of body heat whilst developments in design have ensured extra layering does not equate to extra weight or bulk. Maintaining the trapped warm air between individual layers and within the entire ensemble means understanding venting properties – adjustable cuffs, high neck lines on outer garments, pull-string closures around the hips and close fitting fabrics, alongside the dynamics of body movement and wind effects on clothing, (Havenith, Seames, Metje, Oakes). Fit incorporates the properties of close fabric / body contact (for trapped air warmth and safety when working around machinery), whilst maintaining the capacity for range of movement. Successive layering should not restrict circulation for any part of the body – free movement of all body parts when numbness is first felt will help prevent frostbite, (National Science Foundation). When all of the above parameters have been met, polar adventurers can "....investigate the interaction between the human body, clothing and the environment", p.1 (Xu).

Testing procedures over the fifty years between the first and last papers this author reviewed showed a trend to move away from subjective questionnaires and opinions towards more mathematical and instrumental testing. Whilst the latter provides a more objective, scientific and measurable result, it omits the human factor. This 'humanism' accounts for comfort. Comfort equates to emotional well-being and high emotional well-being determines swifter adaption and greater success at work-related activities in harsh polar environments. Three papers, (Budd, Cena & Metje), used the subjective evaluation method. "It is now widely accepted that the climate chambers used previously fail to provide participating humans with 'experiential realism' in determining thermal comfort," p.1 (Cena, citing Cena and de Dear, 2001). Metje reports, "the complex relationship between physical and psychological parameters on human comfort levels," p.1. Other psychological parameters include previous knowledge of polar conditions and what may be expected when working and living in the cold, knowledge of the layering systems and how to best use them to prevent excessive sweating inside clothing and fitness levels of participants/subjects, to name a few. These are difficult to measure objectively but never-the-less are important values for determining the success of fabrics and clothing prepared for polar use. Continued research into these areas would broaden our knowledge base and direct clothing developments for use in polar conditions.

Conclusions

The first visitors to polar regions, driven by adventure and discovery, relied on native peoples to provide knowledge and experience. Since that first foray into extreme environments our understanding about the science of clothing has developed from subjective testing of subjects using limited testing equipment and facilities, through to objective, validated, mathematical and computer modelling achieved in modern technological facilities.

Researchers have developed our knowledge on thermal insulation and resistance, conduction and convection rates, heat and vapour transmission, external variables to temperature, fabric porosity and permeability, fabric weights and density, fabric design and construction and layering properties. International standards have been adopted for specific measures and testing regimes suitable for this kind of research - systeme international, clo unit, ASTM 1518 -85, DSC and dish techniques.

Thinking has not changed radically in the years between the 1960 and 2008, (the years of publication for research papers used in this review). Keeping warm and dry was critical in historical polar adventures just as it is now. Using the practise of layering clothing helps trap warm air to the body. Keeping sweat and moisture away from the skin and allowing it to vent outside reduces the risk of 'freezing inside your clothes'. What has changed is our technical knowledge of the composition of fabrics and the extent to which we can push those boundaries, the application of mathematical models for chemical and physical processes and the application of these knowledge bases for the advancement of polar clothing.

Further research could include more testing within the field environment people are exposed to – altitude and wind chill, protective substances on shell layers; studying the effect physical fitness and body mass have on sweat and heat production out on the ice; subjective perceptions about radiant temperature versus wind chill factoring – how many layers will I need / shall I take?; comfort ratings within a range of activities and temperatures during a working day.

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